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THE CARBON CYCLE FROM NORTH TO SOUTH ALONG THE GALATHEA 3 ROUTE

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ABSTRACT

Air-sea exchange of CO_2 is parameterized along the cruise track of Galathea 3 – a worldwide research expedition. A key parameter is the gas transfer velocity, which varies with wind speed. Wind speeds are measured continuously on board the research vessel. For selected areas, winds are also retrieved from Envisat ASAR images, as the ASAR senses small-scale waves at the sea surface generated by the local wind. A demonstration from the coastal up-welling zone of Peru shows that CO_2 fluxes are numerically smaller when satellite winds, rather than ship measurements of the wind speed, are used to determine the gas transfer velocity. This difference is likely related to the presence of algae films at the sea surface of the cold and nutrient rich up-welling waters. Algae films have a damping effect on small-scale surface waves and are also believed to hamper air-sea CO_2 transfers. Satellite wind maps may thus be better indicators of the gas transfer velocity than the wind speed at 10 m measured from ships or masts. The relationship between the wind and the CO_2 transfer velocity will be investigated further from a combination of ship and satellite data obtained along the Galathea 3 route.

1. INTRODUCTION

The Danish research expedition Galathea 3 was launched from the harbour of Copenhagen in August 2006 as a follow-up on previous expeditions Galathea 1 (1845-47) and Galathea 2 (1950-52). Fitted with research equipment, the navy vessel 'Vædderen' (Fig. 1) set off on a 9-month worldwide cruise with a total of 100 scientists, journalists and crew members on board.

More than 50 science teams are involved in the Galathea 3 expedition. Among the larger projects is 'The marine carbon cycle from north to south along the Galathea 3 route'. The goal of this interdisciplinary project is to describe the role of the oceans in the global carbon cycle. The World's open oceans are considered to be net absorbers of carbon dioxide (CO_2) from the atmosphere. The oceanic absorption may, to a certain degree, counteract the increasing CO_2 emission from human activities. However, very large uncertainties remain for estimates of the marine carbon budget, especially in near-shore areas where coastal up-welling, river discharge, and wave breaking occur.

Figure 1. The research vessel 'Vædderen'.

In the atmospheric part of the carbon cycle project we focus on the exchange, or flux, of CO_2 between the oceans and the atmosphere and on how these fluxes can be estimated from a combination of ship and satellite measurements. The Galathea 3 expedition covers a wide range of climates from Greenland in the North to Antarctica in the South (Fig. 2). The data collected along the cruise track provide a unique opportunity to estimate CO_2 fluxes globally and to test different methods for the flux retrieval.

Figure 2. Map showing the Galathea 3 cruise track (courtesy the Danish Expedition Foundation).

Ship measurements may be extrapolated in time and space using satellite observations. In contrast to the ship measurements, satellite imagery offer global, year-round coverage. Another major advantage is that satellite observations describe properties of the sea *surface*, where the air-sea gas exchange takes place. Ship measurements are usually obtained at some height above the sea surface or at some depth into the ocean.

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2. CO_2 FLUX PARAMETERIZATION

The air-sea exchange of CO_2 is partly controlled by differences in the partial pressure of CO_2 in the ocean and the atmosphere (ΔpCO_2). The atmospheric CO_2 concentration is approximately 370 ppm all over the globe. A lower CO_2 gas concentration in the ocean would cause a downward flux, as the system seeks to obtain a state of equilibrium. Accordingly, a higher CO_2 gas concentration in the sea would lead to an upward flux.

A bulk parameterization method is used to estimate CO_2 fluxes from measurements of ΔpCO_2:

$$F = k\,\alpha\,\Delta pCO_2 \qquad (1)$$

F is the daily flux of CO_2 (g m^{-2}), k is the gas transfer velocity (m s^{-1}), and α is a coefficient describing the CO_2 solubility in sea water. The gas transfer velocity is closely related to wind speed and several equations exist that describe the k-to-wind relationship (see [1], [2] and references therein). The transfer velocity is usually set proportional to the wind speed at 10 m, as this height is widely used for meteorological measurements. Here we use the relationship of [3] for steady winds to determine the gas transfer velocity. The CO_2 solubility varies according to the temperature and salinity of the ocean, as also described in [3].

3. SHIP MEASUREMENTS

Partial pressures of carbon dioxide (pCO_2) in the ocean and in the atmosphere are measured continuously along the Galathea 3 route. An equilibrator is used to measure the oceanic pCO_2 (Fig. 3). The equilibrator takes in sea water and sprays the water into an air-tight chamber. The CO_2 concentration of the chamber air is measured, once a state of equilibrium is established between the air and the sea water. For the atmospheric pCO_2 measurements, air is taken from an inlet bypassing the equilibrator. All pCO_2 measurements are displayed in near-real-time at www.risoe.dk/galathea.

In order to determine the CO_2 solubility in sea water, the sea surface temperature and the salinity must be known. A ferry box measures these and other properties of the surface water along the Galathea 3 route. Wind speeds are measured continuously with sonic anemometers mounted on both sides of the bridge (Fig. 4). The wind measurements are corrected for the speed and orientation of the vessel. In addition to the parameters entering Eq. 1, we estimate CO_2 fluxes directly using two open path Licors and one closed path Licor mounted on the bridge. A dissipation and covariance method is applied.

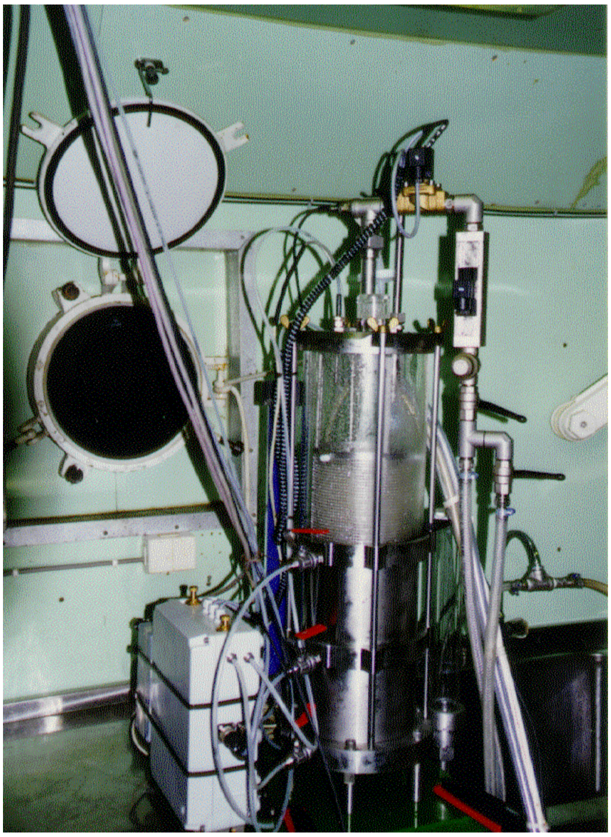

Figure 3. The equilibrator used to measure gas concentrations of CO_2 in sea water.

Figure 4. The equipment mounted on each side of the bridge: a sonic anemometer and a Licor used for direct CO_2 flux estimation from a dissipation and covariance method.

4. SATELLITE DATA

Satellite images are collected along the entire expedition route of Galathea 3. Within the project 'Satellite Eye for Galathea 3', the satellite images are ordered, collected, processed and presented in near-real-time through Google Earth and a Java system (see www.satelliteeye.dk and [4]). Educational material based on the satellite images is published online at http://galathea3.emu.dk/satelliteeye/index_uk.html.

Several Galathea 3 projects use the satellite information in their research. The satellite images show snap-shots of sea surface temperature, sea ice, global ozone, bathymetry, sea level height, ocean winds, ocean wave height, clouds, and land/sea surfaces from both optical and radar sensors. At locations of special interest, such as the harbours, very detailed imagery is collected. The high-resolution data also include chlorophyll maps from Envisat MERIS and wind maps retrieved from Envisat's Advanced Synthetic Aperture Radar (ASAR). Together with sea surface temperature observations, the Envisat MERIS and ASAR data are the most relevant satellite data available for CO_2 flux parameterization.

5. CO_2 FLUXES NEAR THE COAST OF PERU

In the following, we demonstrate how CO_2 fluxes can be parameterized for an up-welling zone off the coast of Peru. The wind is frequently blowing northward along the coast resulting in the rising of cold water to shallower depths. Because of the Coriolis force, surface water is transported at a 90 degree angle to the left of the winds in the southern hemisphere. This is why winds blowing northward parallel to the coastline of Peru tend to 'drag' surface waters westward and away from the shore. Deep waters are generally rich in nutrients and CO_2. Upwelling regions can therefore cause very high emissions of CO_2 in comparison to other parts of the ocean, unless the primary production is able to consume the extra CO_2.

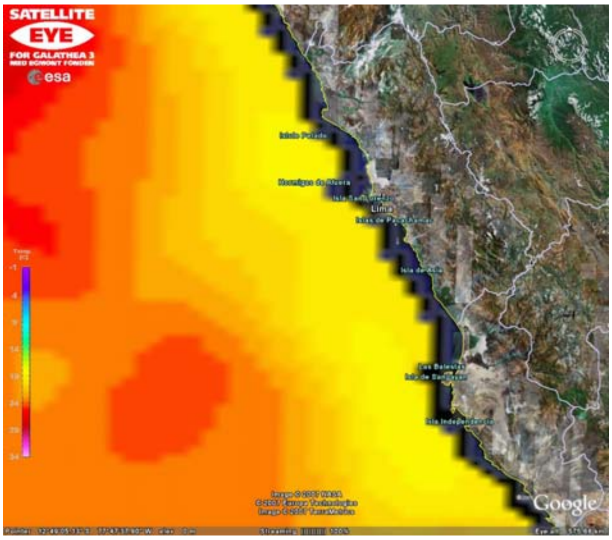

Figure 5. Map showing a sea surface temperature composite from several sensors including Envisat AATSR, 22-25 February 2007. Colder waters near the Peruvian coast show the extent of the coastal up-welling zone.

Fig. 5 shows a 3-day composite of sea surface temperature measurements from several satellite sensors including Envisat AATSR. Temperatures decrease from ~27° C in the deep ocean to ~17 ° C near the Peruvian coast.

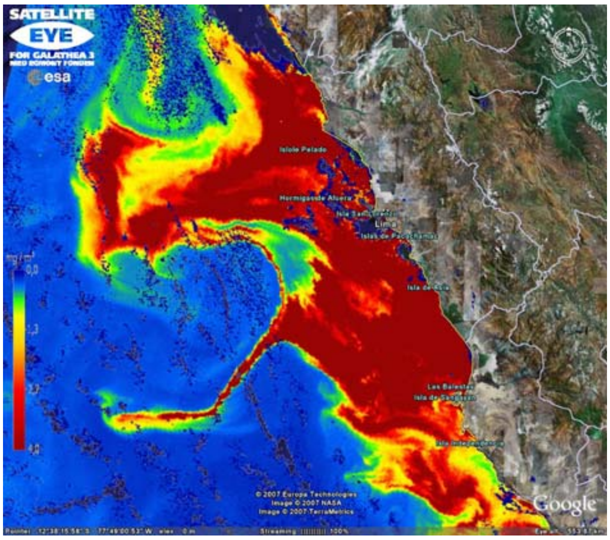

Figure 6. Map showing chlorophyll-a concentrations from Envisat MERIS, 22 February 2007 at 14:42 UTC. High concentrations are found in the coastal up-welling zone of Peru where cold waters, rich in nutrients and CO_2, are forced to the sea surface.

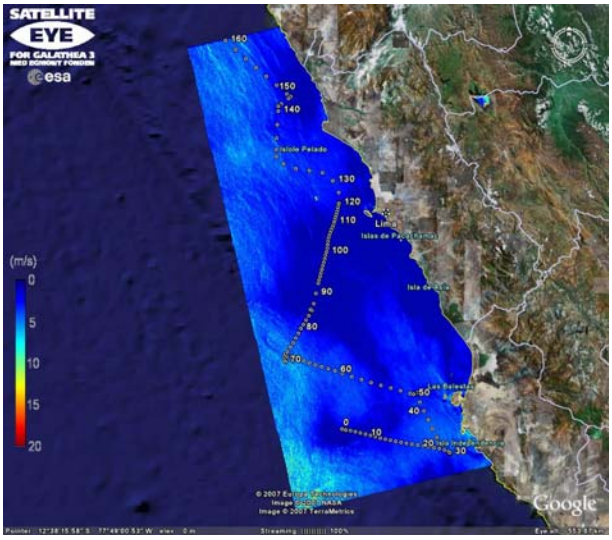

Figure 7. Map showing wind speeds at 10 m retrieved from Envisat ASAR, 26 February 2007 at 03:28 UTC. Winds are from the southwest with relatively low wind speeds (<8 m s^{-1}). Galathea 3 measurement stations are indicated (25-28 February 2007).

Fig. 6 shows a map of chlorophyll-a over Peruvian waters based on Envisat MERIS observations from 22 February 2007. The highest chlorophyll concentrations are found near the coast and indicate an up-welling of cold waters, rich in CO_2 and nutrients. Fig. 7 shows a wind map over the same area generated from Envisat ASAR data a few days later, on 26 February 2007. The wind retrieval relies on capillary- and short-gravity waves at the sea surface. The ASAR sensor measures this small-scale roughness and the empirical model function CMOD5 is applied in order to convert radar backscatter to wind speeds at the height 10 m. We use the ANSWRS software developed at the Johns Hopkins University, Applied Physics Laboratory for this conversion [5].

The presence of algae or other surfactants have a damping effect on small-scale surface waves. Wind maps over algae rich waters may therefore show artificially low wind signatures. We believe this is why large areas of very low wind speeds are seen in Fig. 7.

Laboratory studies have indicated that capillary waves are required for an air-sea gas transfer to take place [6]. The flux is related to the wave steepness, which also determines the radar signature used in satellite wind mapping. Satellite wind maps may thus be a better indicator of surface fluxes than the wind speed at 10 m measured from ships or masts.

The daily flux of CO_2 is estimated from Eq. 1 using ship measurements of wind speed, water temperature and salinity for the period 25-28 February 2007. The measurement stations are indicated in Fig. 7. A second calculation is made where wind speeds are extracted from the satellite wind map, around each station, and used in combination with the ship measurements. This is possible because variations of the wind speed and direction are small for the 4-day period (the satellite image is a snap-shot acquired over only a few seconds). Fig. 8 shows the *in situ* water temperature and the differences in CO_2 partial pressure that enter the parameterization. The resulting CO_2 fluxes are seen in Fig. 9.

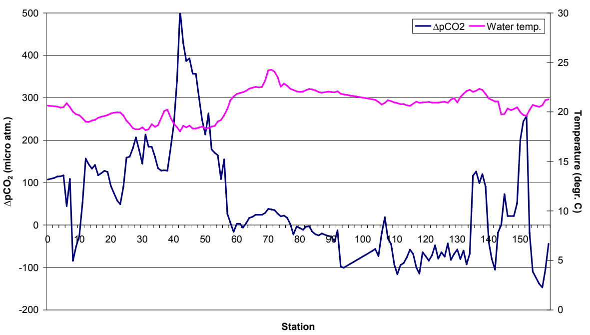

Figure 8. Ship measurements of the difference in CO_2 partial pressure between air and sea (negative values indicate a downward transport) and water temperatures near the sea surface.

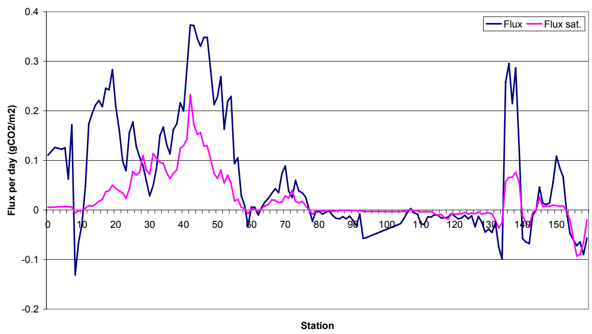

Figure 9. Estimated daily fluxes of CO_2 using ship and satellite measurements of the wind speed, respectively, to determine the gas transfer velocity (k in Eq. 1).

The two figures show how CO_2 fluxes depend largely on ΔpCO_2. Fluxes are numerically smaller when satellite winds are used in the parameterization rather than wind speed measurements from the bridge of the research vessel. For the stations 0-10 and 80-130, the CO_2 flux found from satellite winds is close to zero. This is possibly an effect of algae films at the sea surface, which impact the satellite wind measurements.

A further investigation of the CO_2 fluxes, including the direct micrometeorological flux measurements from the Galathea 3 expedition, is planned. From this investigation we aim to refine existing parameterization schemes for air-sea fluxes of CO_2 to obtain the highest possible accuracy on global flux estimates.

7. ACKNOWLEDGEMENTS

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